Where Are Be/black-hole Binaries?

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ABSTRACT

We apply the tidal truncation model proposed by Negueruela & Okazaki (2001) to arbitrary Be/compact star binaries to study the truncation efficiency dependance on the binary parameters. We find that the viscous decretion disks around the Be stars could be truncated very effectively in narrow systems. Combining this with the population synthesis results of Podsiadlowski, Rappaport and Han (2003) that binary black holes are most likely to be born in systems with orbital periods less than about 30 days, we suggest that most of the Be/black-hole binaries may be transient systems with very long quiescent states. This could explain the lack of observed Be/black-hole X-ray binaries. We also discuss the evolution of the Be/black-hole binaries and their possible observational features.

Subject headings: stars: circumstellar matter, Be - binaries: close - black hole - X-ray: stars, bursts

1. Introduction

X-ray binaries consist of a neutron star (NS) or a black hole (BH) accreting from strong stellar winds or via Roche lobe overflow of the companion star. Depending on the masses of the optical companions, they are conventionally divided into low- and high-mass X-ray binaries. By measuring the radial velocity curve of the non-degenerate donor, the value of the mass function can be determined, which provides a lower limit on the mass of the accreting object. When it is combined with the information of the spectra of the donor and the orbital light curves, actual measurements of the mass can be obtained. In this way, currently the masses of 18 compact objects in X-ray binaries have been found to exceed the the maximum mass possible for a neutron star. These binaries are thought to be black-hole X-ray binaries (BHXBs) (see McClintock & Remillard (2003) and references therein).

Among the 18 BHXBs, 3 are persistently bright X-ray systems and 15 are X-ray novae in which 6 show recurrent outbursts. All of the X-ray novae are low-mass X-ray binaries

(LMXBs). The three persistent sources, i.e. Cyg X−1, LMC X−1 and LMC X−3 are high-mass X-ray binaries (HMXBs) with massive O/B companion stars. In the most recent catalogue of high mass X-ray binaries (HMXBs) edited by Liu, Paradijs & van den Heuvel (2000), only 20 out of 130 HMXBs are O/B supergiant systems including the black hole binaries. Though roughly two thirds of HMXBs are Be/X-ray binaries, and X-ray pulsations have been found in about sixty Be/X-ray binary systems (Ziolkowski 2002), there are no acknowledged Be/BH binaries. The existence of Be/BH binaries becomes an open problem. The solutions may be related to two questions: Do they exist? if yes, how can they be observed?

The first question is connected with the birth-rate estimation of BH/massive X-ray binaries (BMXBs). Using Monte-Carlo simulation, Raguzova and Lipunov (1999) calculated the number and distribution of binary BHs with Be stars. They obtained the expected number of Be/BH binaries to be of order of unity per $20 - 30$ Be/NS systems. The Be/BH binaries were found to be highly eccentric with orbital periods lying in a range of 10 days to several years. The actual number of Be/BH binaries could be even higher since in their work, the lower limit of $50\,M_{\odot}$ for the progenitor of the BH was adopted, based on the mass of the supergiant Wray 977 (Kaper et al. 1995). But current stellar evolution models suggest that stars with mass higher than about $20 - 25\,M_{\odot}$ will result in BHs(Fryer 1999; Fryer & Kakogera 2001). More recently Podsiadlowski et al. (2003) did the binary population synthesis calculation with the mass of the BH progenitors in the range of $25\,M_{\odot} < M_{\rm p} < 45\,M_{\odot}$, and presented the calculated distribution of the orbital period and donor mass for BH binaries in their Fig.2. It is shown that BHs have large possibility to be formed in relatively narrow systems with orbital periods of less than tens of days. The formation rate of BMXBs estimated from their result is about 10^{-5} yr^{-1}. Although the massive donor stars are not constrained to be Be stars in their work, the conclusion of the orbital distribution may also be applied to Be/BH binaries, since the fraction of the Be stars to the massive stars is not small (see Coe (2000) and references therein). Nevertheless, theoretical estimation of this fraction is difficult. It is not yet clear how Be stars eject the circumstellar envelope. While rapid rotation plays a part in disc creation, it is not the sole cause (Porter 1999). Whether the physical properties of the donor star (metallicity, instability in the photosphere induced by binary rotation, and etc.) have effects on producing the dense disk winds is still unknown (Zamanov et al. 2001).

The observation of supergiant B[e]/BH system, e.g. XTE J0421 + 560/CI Cam (Robinson, Ivans & Welsh 2002), may provide a further proof of the existence of Be/BH binaries, since theoretically sgB[e]/X-ray binaries would have less probability to exist than Be X-ray binaries due to the much larger mass of sgB[e] stars. Thus, the absence of Be/black-hole binaries might be due to some observational selection effects. In this work, we try to find

the clue of the second question, that is, why we can hardly observe them. We would start from the interaction between a Be star and its compact companion.

Be/X-ray binaries are characterized by their transient nature. Recently, theoretical work on disc truncation in Be/X-ray binaries (Okazaki & Negueruela 2001; Okazaki et al. 2002) was invoked to explain the X-ray outbursts in Be/X-ray binaries, and has got considerable success in the application to several systems (Okazaki & Negueruela 2001), especially 4U 0115+63/V635 Cas (Negueruela & Okazaki 2001) and A0535+26 (Haigh, Coe & Fabregat 2003). The key idea is as follows: The neutron star exerts a net negative tidal torque on the viscous decretion disk of the Be star, diminishing the action of the viscous torque outside some critical radius, and thus resulting in the truncation of the disk. The disc matter would then accumulate in the outer rings of the disk till overcoming of the truncation by the effects of global one-armed oscillations or disk warping, etc. The following sudden infall of high density disk matter onto the neutron star causes type II X-ray outbursts. During the episodes between the outbursts, the neutron star could hardly be observed because of low mass accretion rate or the propeller effect. On the other hand, if the tidal truncation is not very efficient, and the disc can extend beyond the Roche lobe of the Be star at periastron, the matter could be accreted onto the neutron star during the periastron passage, resulting in (quasi-)periodic type I bursts.

It is interesting to see what would happen when the neutron star in the above picture is replaced by a black hole. We extend the application of this theory to arbitrary systems to find the influence of mass ratio, orbital period, eccentricity and viscosity coefficient on the efficiency of disc truncation. The model and the necessary parameters are briefly described in section 2. The results are shown in section 3. Our discussion and conclusions are made in section 4.

2. Model

Negueruela & Okazaki (2001) suggest a scenario for the behavior of Be/X-ray binaries based on long-term multiwavelength monitoring and two theoretical models: (1) the viscous decretion disk of Be stars proposed by Lee, Saio & Osaki (1991), where the mass flow is outward in contrast with that in accretion disk, and angular momentum of the disk is added by viscous torque $T_{\rm vis}$; (2) the tidal truncation model investigated by Artymowicz & Lubow (1994) for the gravitational interaction of an eccentric binary system with circumstellar or circumbinary disks.

Following Negueruela & Okazaki (2001), we consider the picture of the Be/X-ray binary

in which the compact star of mass $M_{\rm x}$ moves around a Be star of mass M_* and radius R_* in an orbit of eccentricity e, exerting resonant torques $T_{\rm res}$ on the Be decretion disk. As first approximation, the disc is assumed to be coplanner. The criterion for the disc truncation at a given resonance radius $r_{\rm trunc}$ is

$$T_{\rm vis} + T_{\rm res} \leq 0, \tag{1}$$

where $T_{\rm res}$ can be easily shown to be dominated by the torque of the inner Lindblad resonance $T_{\rm res} \simeq \sum_{ml}(T_{\rm ml})_{\rm ILR}$. For near-Keplerian discs, given the expression of viscosity and resonance torques as Eqs.(6) and (8) in Negueruela & Okazaki (2001), the above truncation criterion can be approximated as

$$Re^{-1} = \alpha(\frac{H}{r})^2 \leq \frac{\pi a^2}{(GM_*)^2(1+q_{\rm x})^{2/3}n^{4/3}\sum_{ml}\frac{m^3}{m-1}|\phi_{\rm ml}|^2}, \tag{2}$$

where the radius of the inner Lindblad resonance is $r = ((m-1)/l)^{2/3}(1+q_{\rm x})^{-1/3}a$, α is the Shakura-Sunyaev viscosity parameter, a is the semmimajor axis of the binary orbit, and $q_{\rm x} \equiv M_{\rm x}/M_*$. The Reynolds number Re is determined by the thermal structure of the disk.

In our calculation, an isothermal disc with $c_{\rm s}/V_{\rm k}(R_*) \sim 4.1\times10^{-2}(T_{\rm d}/T_{\rm eff})^{1/2}$ is assumed as in Okazaki & Negueruela (2001), where $c_{\rm s}$ is the sound speed of the disk, $V_{\rm k}$ is the Keplerian velocity, and the disk temperature $T_{\rm d}$ is about 1/2 of the effective temperature $T_{\rm eff}$ of the Be star. For a Keplerian disk, the scale height H of the disk is then

$$\frac{H}{r} = \frac{c_{\rm s}}{V_{\rm k}(R_*)}(\frac{r}{R_*})^{1/2}. \tag{3}$$

We adopt $R_*/R_\odot \approx (M_*/M_\odot)^{0.8}$ to get the corresponding radius of the donor star.

The key function in the criterion (2) is the potential component $\phi_{\rm ml}$, which can be expressed as

$$\phi_{\rm ml} = -\frac{GM_{\rm x}}{a}\frac{1}{\pi}\int_0^\pi df\frac{(1-e^2)^{1/2}}{1+e\cos(f)}\cos(mf-n(m-1)M(f))b^m_{1/2}(r/r_2(f)), \tag{4}$$

where

$$b^m_{1/2}(x) \equiv \frac{2}{\pi}\int_0^\pi\frac{\cos m\varphi d\varphi}{\sqrt{1-2x\cos\varphi+x^2}} \tag{5}$$

is the Laplace coefficient with argument $x = r/r_2$, and $r_2 = a(1-e^2)/(1+e\cos(f))$ is the distance of the compact star from the donor star. To make it convenient to solve the integration in $\phi_{\rm ml}$, we have used the following relations among the mean anomaly M, the true anomaly f and the eccentric anomaly E in an orbital ellipse,

$$dM/df = (1-e^2)^{3/2}/(1+e\cos(f))^2 \tag{6}$$

$$M = E - e \sin E \tag{7}$$

$$\sin E = \frac{r_2 \sin f}{a\sqrt{1-e^2}} = \frac{\sqrt{1-e^2}}{1+e\cos f} \sin f. \tag{8}$$

From Eqs. (7) and (8), we get

$$M(f) = \begin{cases} \arcsin(z(f)) - e \cdot z(f), & \text{if } \ 0 \le f < \arccos(-e); \\ (\pi - \arcsin(z(f))) - e \cdot z(f), & \text{if } \ \arccos(-e) \le f \le \pi \end{cases} \tag{9}$$

where $z(f) = (1-e^2)^{1/2} \sin f/(1 + e\cos f)$. Inserting $M(f)$ to equation (4), the numerical integration can be done directly.

In the calculation of the truncation criterion (2), $l = n(m-1)$ for the inner Lindblad resonance, the parameter of the summation is only m then. Because the high order components contribute little, we sum the inner Lindblad resonance torque from $m = 2$ to the value at which the component is three orders smaller than that of $m = 2$. The truncation radius deduced from the inner Lindblad radius is then

$$r_{\text{trunc}} = n^{-2/3}(1+q_{\text{x}})^{-1/3}a = n^{-2/3}(GM_*/(2\pi/P_{\text{orb}})^2)^{1/3}. \tag{10}$$

The timescale to open the gap between r_{trunc} and the inner Lagrangian point d_{L1} with $\Delta r = d_{\text{L1}} - r_{\text{trunc}}$, is about $t_{\text{open}} \approx Re_{\text{crit}}(\Delta r/r_{\text{trunc}})^2 P_{\text{orb}}/2\pi$ as in Artymowicz & Lubow (1994), where $Re_{\text{crit}} = \alpha_{\text{crit}}^{-1}(H/r)^{-2}$ denotes the Reynolds number for which the gap is opened from r_{trunc}. Since the outflow in the disc is subsonic (Okazaki & Negueruela 2001), the timescale $\tau_{\text{drift}} \sim \Delta r/v_{\text{r}}$ of a particle drifting from r_{trunc} to the Roche lobe will be longer than the truncation timescale. Thus, the efficient truncation is defined as (Okazaki & Negueruela 2001)

$$\gamma \equiv (\tau_{\text{drift}}/P_{\text{orb}})_{\min} \sim \Delta r/(0.1 c_{\text{s}} P_{\text{orb}}) > 1 \tag{11}$$

where $v_{\text{rmax}} \sim 0.1c_{\text{s}}$ and $d_{\text{L1}} = (0.500 - 0.227 \lg q_{\text{x}})a(1-e)$ - the distance of the inner Lagrangian point point from the center of the donor (Frank, King & Raine 2002) at periastron have been used instead of the Roche radius, since it is the flat disk rather than the star itself expanding to the Roche lobe.

3. Result

To study the influence of mass ratio, orbital period, eccentricity and viscosity coefficient on the efficiency of disc truncation, we have calculated the cases with $M_{\text{x}} = 1.4, 10\,M_\odot$, $M_* = 6, 15, 20\,M_\odot$, $P_{\text{orb}} = 5, 30, 100, 250\,\text{d}$, $\alpha = 0.03, 0.1, 0.3$ and $e = 0.01, 0.05, 0.1, 0.3, 0.5, 0.7$. The masses of the Be star and the orbital periods are chosen according to Fig. 2. of

Podsiadlowski et al. (2003) and the observations of HMXBs. It is shown in their figure that most BH X-ray binaries are born in orbits with $P_{\rm orb} < 30\,{\rm d}$ and $M_* < 15\,M_\odot$. On the other hand, most observed Be/NS binaries have the donor stars with masses of about $10-20\,M_\odot$, and orbital periods lying in the range of $16\,{\rm d} < P_{\rm orb} < 300\,{\rm d}$. The viscosity coefficient and the eccentricity are adopted for convenient comparison with the result in Table 2 of Okazaki & Negueruela (2001).

The calculated values of the truncation efficiency criterion $(\tau_{\rm drift}/P_{\rm orb})_{\rm min}$ are shown against the eccentricity in Figs. 1, 2 and 3 with $M_* = 6, 15, 20\,M_\odot$ respectively. The data of different $P_{\rm orb}$ are grouped. The general features of the figures can be summarized as follows:
(1) the smaller viscosity parameter of the disk, the more efficient truncation (it can be understood from equation (1) that, given the resonance torques by the compact star, discs of weak viscosity are truncated at small radius);
(2) the narrower systems, the more efficient truncation, since $\gamma \propto a/P_{\rm orb} \propto {P_{\rm orb}}^{-1/3}$;
(3) for systems with $e > 0.1$, smaller e leads to more efficient truncation, because of the corresponding larger distance to the inner lagrangian point at periastron;
(4) the larger mass of the compact star have a little less effective truncations on the disk of Be star (since $d_{\rm L1}$ of Be star is smaller for more massive companion stars, whereas $r_{\rm trunc}$ has no relation to $M_{\rm x}$ as shown in equation (10)); discs of more massive Be stars would be truncated more effectively, especially when $e < 0.4$.

Features (1) and (3) have been found in Okazaki & Negueruela (2001), and the viscous effect has been studied in detail by 3D SPH simulations in Okazaki et al. (2002). However, feature (2) was neglected. It is shown in our figures that the influence of the orbital period on the disk truncation is the most promising one among the parameters. Although feature (4) shows that black holes would not have more effective truncation on the decretion disk of the Be stars than neutron stars, with the help of feature (2), we know that if Be/BH binaries are mostly born in narrow systems, effective truncation would still happen (except for very eccentric systems), so that the accretion would be mainly from the polar wind of the donor star.

4. Discussion and Conclusion

We have extended the application of Be disk truncation model proposed by Negueruela & Okazaki (2001) and Okazaki & Negueruela (2001) to general Be binary systems, to study the dependance of truncation efficiency on some basic binary parameters, such as the stellar mass, viscosity coefficient, orbital period and eccentricity. The results not only confirm the

trend that low viscosity and small eccentricity would lead to effective Be disk truncation (Okazaki & Negueruela 2001), but also show that most effective truncation would occur in relatively narrow systems.

The above results can help us to understand the observations of Be binaries. In the context of Be/NS binaries, the observed transient features of the wide ($P_{\rm orb} \sim 17 - 263$ d) eccentric ($e \sim 0.1 - 0.9$) systems can be well understood by the disk truncation effect. Furthermore, the results also presents a possible explanation for the absence of Be/BH binaries if they are formed in relatively narrow orbits without high eccentricity, as suggested by Podsiadlowski et al. (2003). The relatively narrow orbit of $P_{\rm orb} < 30\,{\rm d}$ is supported by the result of binary population synthesis simulation work of Podsiadlowski et al. (2003) with the assumption of circular orbit. The knowledge of the eccentricity could be traced back to the formation of the BHs in the massive binaries. The BHs were born from the collapse of massive stars in two different ways (see Fryer (1999) and reference therein). (i) The massive stars directly collapse into black holes. (ii) After supernova explosion, a significant part of the stellar matter falls back onto the proto-neutron star forming a black hole. If there were no kick in the latter case, the eccentricity induced by the supernova can be estimated by $e = \Delta M/M_{\rm f}$ (Bhattacharya and van den Heuvel 1991), where ΔM is the total mass loss from the binary in the supernova explosion, and $M_{\rm f}$ is the final mass of the binary. Assuming the mass of the secondary star change little during the process, one can expect less ΔM and larger $M_{\rm f}$ in black hole binaries, resulting in smaller eccentricity compared to neutron star binaries. The spatial distribution and the kinematics of most of the black-hole binaries appear to be consistent with the assumption that small asymmetric kicks are imparted to the black holes (White & van Paradijs 1996), with at least one exception GRO J1655-40, the first black hole system which has evidence of runaway space velocity of $112 \pm 18\,{\rm km\,s^{-1}}$ in an orbit of $e = 0.34 \pm 0.05$ (Mirabel et al. 2002).

Because of very effective tidal truncation on Be disks in the relatively narrow and low eccentric systems, the flow of the matter towards the BH will be effectively blocked during almost the whole orbital cycle. In such episode, the accretion could be mainly from the polar wind of the donor star. As suggested by Waters & van Kerkwijk (1989), the polar wind of the Be star probably resembles that in OB stars. Such low-density high-velocity wind can hardly form accretion disks around the BHs, and the accretion would follow the classical Bondi-Hoyle-Littleton (BHL) approximation. For a typical main-sequence $15\,M_\odot$ main-sequence star in the system of $P_{\rm orb} = 10\,{\rm d}$, if the mass loss rate $\dot{M}_{\rm w} = 10^{-9}\,M_\odot\ {\rm yr}^{-1}$ and the terminal wind velocity $v_\infty = 2000\,{\rm km\,s^{-1}}$ exist, the accreting compact star would have luminosity of about $L_{\rm x} \sim 10^{33}\,{\rm erg\,s^{-1}}$. For the Be/BH binaries, the luminosity would be still less, since the polar wind just takes a small fraction of the mass loss from the donor star. The wind plasma accumulates in the outer rings of the decretion disc till one-armed

oscillaiton instability - probably responsible for the V/R variability seen in the Be stars - occurs, which causes the almost total disruption of the Be disk. The resulted large mass-infall onto the black hole would lead to very luminous outbursts. However, no aspect of the truncation model implies that the large mass transfer must occur (Okazaki et al. 2002). If the collapsed disk due to the dynamical instability falls back on to the more massive Be star, such narrow and low-eccentricity transients would be almost out of detection even for the most sensitive instruments, so it should be careful to deal with the Be stars unrelated to the X-ray sources.

For systems in which effective truncation occurs, e.g. XTE J1543−568 and 2S 1553−542, the burst activities are very rare (see Okazaki et al. (2002) and reference therein). During the long quiescent stage, Be stars could be identified from the Balmer (and sometimes other) line emission and the associated strong infrared excess. In the HMXB catalogue of Liu, Paradijs & van den Heuvel (2000), there are probably 24 Be/X-ray systems where the nature of the compact star and the orbital period are undetermined. They are signed as Be/X-ray binaries because of their highly variable X-ray characteristics analogous to those of the well studied Be/NS transients, or the optical identification of the donor stars. Most of them have been observed once during the burst states, and then disappeared from X-ray detection because of very low luminosity. Among these undetermined Be/X-ray systems, XTE J1739 − 302 and AX J0052.9 − 7158 (SMC 32) can be excluded now since the donor star of the former has been identified as an O supergiant (Smith et al. 2003) and 167.8 seconds pulsations have been found in the latter (Yokogawa et al. 2001). To look for Be/BH binaries in the left systems, optical observations in the quiescent stage become important, from which we can confirm the nature of the donor star and get information of the orbital period and the velocity curve of the donor. The latter two are useful in estimating the dynamical mass of the compact star - the common way to determine whether the compact star is a black hole, though the measurements would be very difficult in Be/X-ray binaries, because of not only the relatively low velocity of the donor but also the variability of the circumstellar envelope of Be stars (Raguzova and Lipunov 1999). The accurate locations of some of the undetermined Be/X-ray binaries could be derived with Chandra, which will enable following up observations in the infrared/optical wavelength. Till now, we have found very limited data of these faint Be/X-ray binaries, and there is at least one system GRS 1736 − 297 went undetected even in the Chandra observations (Wilson et al. 2003).

Even if the X-ray outbursts due to the large mass inflow from the erupted disks are observed, it is still difficult to distinguish between black holes and neutron stars, unless pulsations have been found in the latter. Although there is growing evidence that black hole X-ray binaries display radio emission when they are in the low/hard X-ray state (Reig, Kylafis & Giannios 2003), this is not a decisive criterion. LS I+61°303 is an example, whether

the compact star is a neutron star (Zamanov 1995) or a magnetized black hole (Punsly 1999) is still in debate.

Be stars can be distinguished from normal O/B stars by the special dense disk wind structures when they are on the main sequence. Once they evolve to fill the Roche lobe, they can hardly be distinguished. Due to the high mass transfer rate from the Roche lobe overflow, black holes in HMXBs would be extremely luminous, even well above the Eddington limit $L_{\rm Edd}$ for a stellar-mass black hole, resulted from either the beaming effect (King et al. 2001) and/or being genuinely super-Eddington (Begelman 2002), and thus become ones of the ultra luminous X-ray sources (ULXs). This can also be seen in fig. 6. of Podsiadlowski et al. (2003).

Finally, we conclude that by investigating the disk truncation efficiency in Be/compact star binary systems, we propose a possible explanation for the absence of the observation of Be/BH binaries. We show that if most of the Be/BH binaries are born in relatively short low eccentric orbit, the interaction of the binary stars will lead to very effective truncation on the decretion disk around the Be star, so that most of the Be/BH systems would appear as very low luminous X-ray sources.

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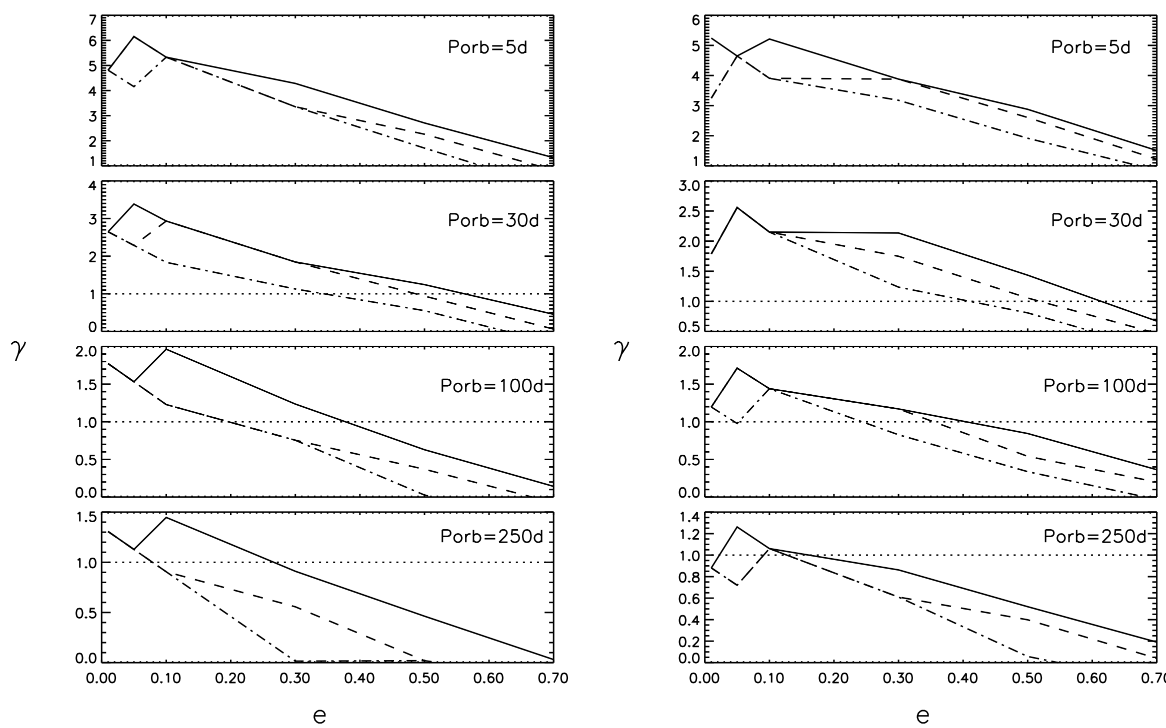

Fig. 1.— Eccentricity dependence of the truncation efficiency $\gamma \equiv (\tau_{\rm drift}/P_{\rm orb})_{\rm min}$ for Be/neutron star binaries (left) and Be/black-hole binaries (right) with Be star mass $M_* = 6\,M_\odot$. The full lines, dashed lines and dash-dotted lines are obtained with the disk viscosity parameter $\alpha = 0.03, 0.1, 0.3$, respectively. Dotted lines of $\gamma = 1$ are drawn for comparison. We delete the point of $\gamma(e) < 0$, since the negative values represent the ineffective truncation with $r_{\rm trunc} > r_{\rm L1}$ and thus have no physical meaning.

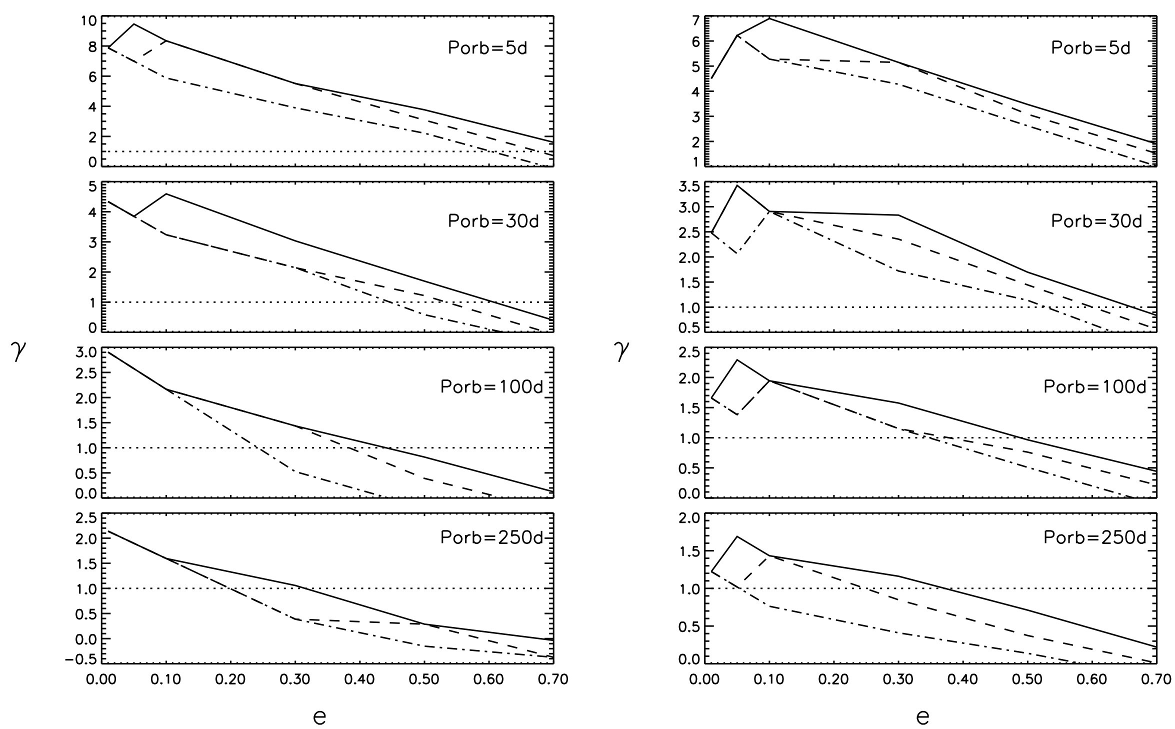

Fig. 2.— Same as in Fig.1, but with $M_* = 15\,M_\odot$.

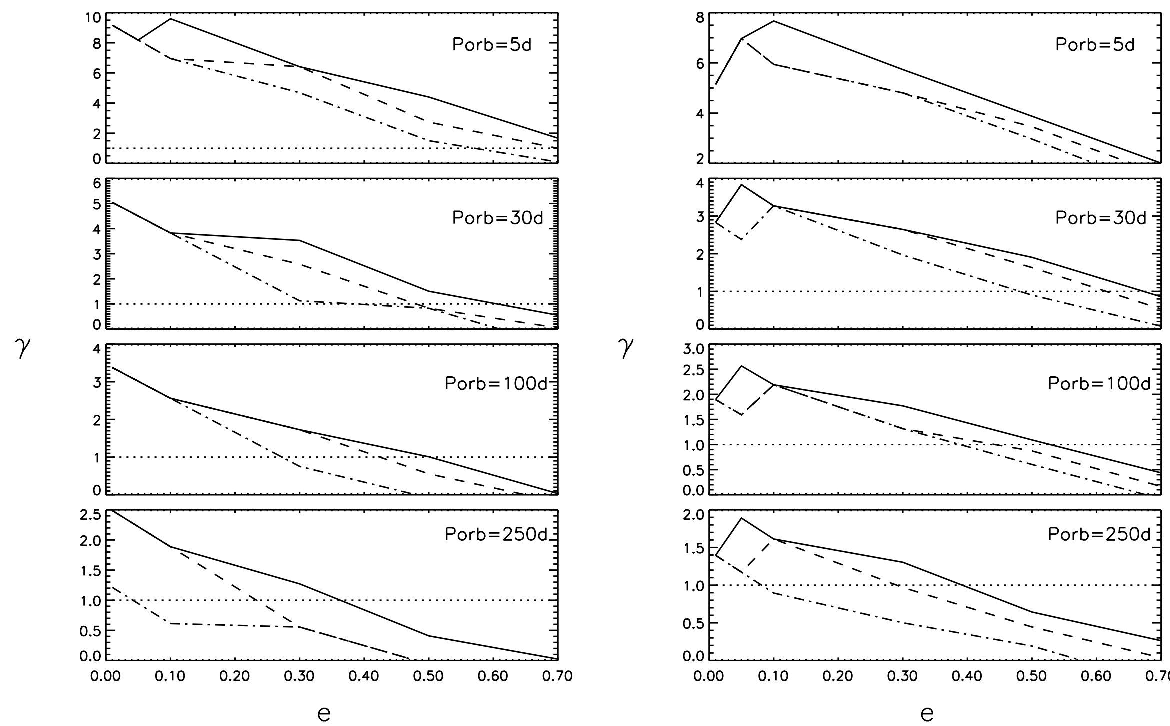

Fig. 3.— Same as in Fig.1, but with $M_* = 20\,M_\odot$.